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著者	萩原 喜昭
著者別名	Yoshiaki Hagiwara
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論文

Extragalactic Astronomical Masers IV - Recent results of sub-millimeter maser observations

Yoshiaki Hagiwara*

Abstract

We report the results of recent observations of sub-millimeter H_2O maser using Atacama Large Millimeter/sub-millimeter Array (ALMA) in Chile. The 22 GHz (corresponding to a wavelength of 1.3 cm) extragalactic H_2O maser that radiates strong emission is known to be a most powerful tool for studying inner parts of active galactic nuclei, while other H_2O masers observed at higher frequencies such as sub-millimeter masers have not been well studied to date. The recent progress of observational technique at sub-millimeter wavelengths (at $\lesssim$ 1 mm wavelength) with ALMA has made it possible to explore the sub-millimeter masers more efficiently. Utilizing the archival science data of ALMA, the spectral data analysis of observations of sub-millimeter H_2O masers in the 321 GHz, 325 GHz, and 658 GHz transitions toward three active galaxies exhibiting known 22 GHz H_2O masers has been made. According to our analysis, no maser emission has been detected towards the galaxies. No detection of the maser could be due to intensity variability of the maser, or insufficient physical condition that is necessary for exciting the maser in the galaxies.

keywords: Molecular gas, maser, active galactic nucleus, sub-millimeter, radio interferometry

* 5-28-20 Hakusan, Bunkyo-ku, Natural Science Laboratory, Toyo University, Tokyo

1 Introduction

Maser (Microwave Amplification by Stimulated Emission of Radiation) is microwave version of optical ”laser” which stands for Light Amplification by Stimulated Emission of Radiation. Cosmic maser radiation that naturally occurs both in star-forming sites in our own Galaxy and external galaxies has been reviewed in Paper I [8] and Paper II [10], where 22 GHz H_2O maser is explained as the most promising tool for tracing inner parsecs of active galactic nuclei (AGN), and Paper III [11] in which the short introduction of sub-millimeter maser is presented. About twenty H_2O masers in different transitions (or at frequencies) are found in our Galaxy, of which 22 GHz H_2O maser is one of the best-studied maser. The 22 GHz (λ = 1.3 cm) H_2O maser has been established as a tool for tracing bipolar molecular outflows (gas motion in stars that appears in star-forming process) in massive star-forming regions in our Galaxy, while the H_2O masers found in AGN are known to trace sub-parsec scale kinematics of active nuclei. Of the H_2O masers found in AGN, some fraction of them are categorized into ”nuclear maser” that probes the inner parsecs of AGN. One may wonder if H_2O maser emission in other transitions, particularly that at sub-millimeter wavelength ($\lambda \lesssim 1$ mm) can probe dense molecular gases, molecular discs, or tori in AGN.

As a reference, the brief history of the sub-millimeter maser studies is summarized in table 1. Recently, H_2O masers in external galaxies, what we call extragalactic masers or megamasers, have been found one after another in active galaxies [7, 9, 14], owing to greatly improved sensitivity of observations using ALMA (Atacama Large Millimeter/sub-millimeter Array). Consequently, the extragalactic H_2O maser has become no longer particular case of maser emission since about a decade ago.

In this article, the preliminary data analysis of the recent observations of

sub-millimeter H_2O masers towards AGN using the archived data of ALMA is briefly presented.

2 Data analysis

In ALMA Science Archive [2], we found the archived data of sub-millimeter H_2O masers towards three galaxies, ESO 558-G009, IC 2560, and NGC 5765, all of which were observed in same periods of 2016 February to August in the compact configuration of ALMA. The observed masers are at frequencies of 321.226 GHz (0.9 mm), 325.153 GHz (0.9 mm), and 658.007 GHz (0.45mm) transitions. The properties of the observed galaxies are summarized in table 2. Data calibration was performed using the Common Astronomy Software Applications (CASA). Amplitude calibration or flux density calibration was performed using planets or quasars based on standard methods, and the bandpass correction was made with the quasar 3C 454.3. The observations were made with dual-polarization bands of 1.875 GHz bandwidth each, divided into 3840 spectral points, yielding the spectral resolution of 488.3 kHz, that corresponds to about 0.46 km s^{-1} at 321 GHz, 0.45 km s^{-1} at 325 GHz, and 0.22 km s^{-1} at 658 GHz. A resultant total velocity coverage is ~ 1766 km s^{-1}, 1738 km s^{-1} , and 858 km s^{-1}, respectively. Below, basic properties of the three galaxies are briefly broken down.

ESO 558-G009 ESO 558-G009 having an active nucleus exhibits the nuclear maser at 22 GHz, whose distribution was imaged with VLBI (Very Long Baseline Interferometry). The position-velocity map of the maser obtained by VLBI reveals Keplerian rotation curve in the center of the galaxy [3]. The spectra of the 22 GHz maser strongly indicate presence of a rotating maser disc in the galaxy, which is categorized a “clean disc”. For these reasons, the galaxy is

considered to be one of the most important targets of Megamaser Cosmology Project undergoing at the NRAO (National Radio Astronomy Observatory) [13].

IC 2560 IC 2560 hosts a type 2 Seyfert nucleus in the center of the galaxy and the 22 GHz maser spectra having Doppler-shifted components indicate a compact Keplerian disc around the nucleus [5, 12]. The highly obscured nucleus surrounded by neutral gas is measured by hard X-rays, that results in the detection of higher column density (Compton-thick) [6].

NGC 5765 NGC 5765b (hereafter, NGC 5765), in a galaxy pair with NGC 5765a, has a type 2 Seyfert nucleus and has 22 GHz water maser in the center of the galaxy. VLBI observations of the maser have shown Keplerian rotation curve in the galaxy, suggestive of the presence of a rotating disc in the nucleus [4].

3 Results

Figures 1 and 2 display water maser spectra at ALMA band 7 and 9 (321 GHz, 325 GHz, and 658 GHz) towards ESO 558-G009, IC 2560, and NGC 5765. These spectra do not show any emission in any of the transitions. Rms sensitivities of each spectrum range from 1 to 5 mJy beam^{-1} (see table 2). Isotropic luminosity of maser can be estimated using the expression given below [15],

$$L_{\mathrm{H_2O}} = 0.00104 \times \frac{\nu}{[GHz]} \frac{D^2}{[Mpc^2]} \frac{\int S\nu \, dv}{[Jy\ km/s]} L_{\odot} \tag{3.1}$$

, where ν is a rest frequency in GHz, D is a distance to the galaxy in Mpc, and $S\nu$ is the flux density in Jy (Jansky). Given the distances to ESO 558-G009 of 107 Mpc, IC 2560 of 44.5 Mpc, and NGC 5765 of 116 Mpc and by adopting rms noises in table 2, 3σ upper limits for isotropic luminosity of the 321 GHz maser

are calculated to 10.5 $L_{\odot}$,1.8 $L_{\odot}$, and 6.3 $L_{\odot}$. Similarly, the 3σ upper limits for the 325 GHz maser luminosity of ESO 558-G009, IC 2560, and NGC 5765 are estimated to 36.6 $L_{\odot}$, 2.7 $L_{\odot}$, and 9.0 $L_{\odot}$. Likewise, the upper limit luminosity for NGC 5765 at 658 GHz is 30.3 $L_{\odot}$.

4 Discussion

Interpretation of our no detection of the sub-millimeter maser towards the three galaxies that exhibit known 22 GHz maser is not straightforward. Given the upper limit luminosity of 1.8 – 36.6 $L_{\odot}$, it is clear that in these galaxies there is no intense megamaser emission whose isotropic luminosity is six orders of magnitude larger than that of Galactic maser in star-forming sites. The three galaxies are selected from megamasers that exhibit relatively strong H_2O maser at 22 GHz, however we could not detect maser at sub-millimeter wave lengths. Contrary to that, 321 GHz H_2O masers are distinctly detected towards the two AGN, Circinus galaxy and NGC 4945 [7, 9, 17], both of which show strong 22 GHz H_2O megamaser emission. It should be noted that the 321 GHz H_2O masers show clear intensity variability similar to that of 22 GHz H_2O maser in these galaxies.

It might be that the no detection could be due to intensity variability of maser that is typically seen for other sub-millimeter masers.

As discussed in Paper III, the luminosity of the 183 GHz maser (~ 1000 $L_{\odot}$) in NGC 4945 is approximately three orders of magnitude higher than the 321 GHz maser in the galaxy [15], possibly because the 321 GHz water maser (E_u/k = 1862 K) is not sufficiently excited compared with H_2O maser in the 183 GHz transition (Eu/k = 205 K). Thus, we can speculate that if the 183 GHz maser were observed, the 183 GHz maser would have been detected towards these galaxies. Moreover, observation of 325 GHz maser could be problematic due to

atmospheric absorption as the maser frequency is closer to that of water vapor lines in atmosphere, although which depends on redshift of each galaxy.

5 Summary

We analyzed the ALMA Science Archive data of sub-millimeter H_2O masers towards three active galaxies hosting known 22 GHz H_2O masers, and found no distinct emission at the rms noises of 1-5 mJy. The interpretation of our no detection is not straightforward, however, which could be due to intensity variability of maser reported in sub-millimeter H_2O masers in other galaxies. Further observations by considering timing of intensity variability of H_2O maser in other transitions such as 22 GHz or 183 GHz might lead to successful detection of sub-millimeter masers in the galaxies.

This paper makes use of the following ALMA data: ADS/JAO.ALMA #2013.1.00824.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Table 1: Brief history on the studies of extragalactic sub-millimeter water maser

Year	Event	Reference
2004	Detection of the 183 GHz H_2O maser in the LINER galaxy NGC 3079	[14]
(2011	ALMA started sub-millimeter maser observations)	
2013	The first detection of 321 GHz H_2O maser in Circinus galaxy	[7]
2014	The long baseline campaign of ALMA conducted at ~ 0.02" resolution	[1]
2016	The first detection of 325 GHz H_2O emission towards the nucleus of the merger galaxy Arp 220	[16]

Table 2: List of the observed galaxies and maser transitions

Galaxy	RA (J2000)	Dec (J2000)	$V_{sys,lsr}$ (km/s)	Frequency (GHz)	Day (m/yy)	Rms (mJy/b)
ESO558-G009	07:04:21.0	-21:35:19.4	7655	321,325	2,3/16	2, 7
IC2560	10:16:18.6	-33:33:49.8	2913	321,325	2,8/16	2, 3
NGC5765	14:50:51.5	+05:06:52.2	8342	321,325,658	3,7/16	1, 1.5, 5

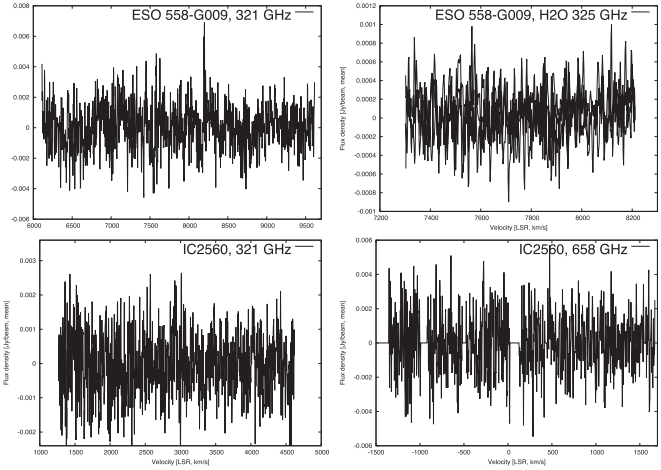

Fig. 1: Plots of maser spectra of ESO 558-G009 and IC 2560 in the 321, 325, and 658 GHz transitions are presented. Vertical axes are flux density scaled in Jansky (10^{-26} W m^{-2} Hz^{-1}) and horizontal axes are velocity in km s^{-1}. The velocity of the 658 GHz spectra of IC 2560 is centered at or near the galaxy's systemic velocity.

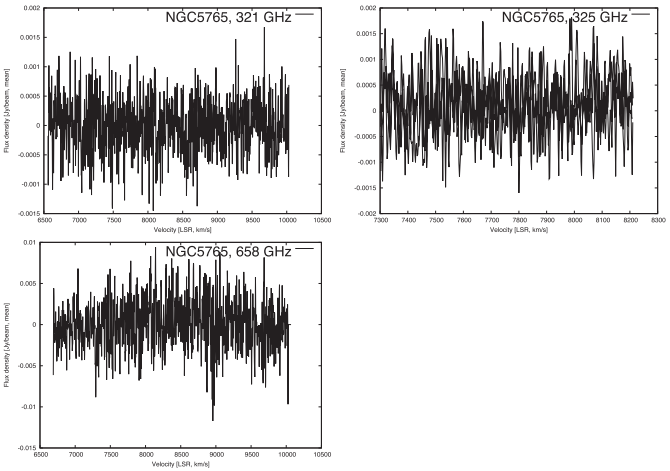

Fig. 2: Plots of maser spectra in NGC 5765 in the 321, 325, and 658 GHz transitions are displayed. Axes are scaled in the same way as in figure 1.

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